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DHS-STEM Summer Internship Report

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Over the course of the last twelve weeks, I have been contributing to efforts in high efficiency solid state thermal neutron detection at Lawrence Livermore National Laboratory (LLNL) as a DHS HS-STEM intern. Reliable, high efficiency solid state thermal neutron detectors are desired to replace conventional ^{3}He gas filled tube technologies which have fieldability issues due to size, high operating voltage requirements, sensitivity to microphonics, and the recently rapidly diminishing supply of ^{3}He gas. Under the supervision of Rebecca Nikolić and Qinghui Shao, I have been developing an experimental plan to modify the doping profile of LLNL's silicon-based pillar structured thermal neutron detector. The overall goal of this work is to reduce the capacitance and leakage current of the *Pillar* detector to enable the device area to be increased while maintaining a high thermal neutron detection efficiency.

LLNL's pillar structured thermal neutron detector is a charge-based detection platform. The detector utilizes a three-dimensional design with high aspect ratio Si p-i-n pillars, fabricated using standard photolithography and reactive ion etching, and neutron reactive boron-10 (^{10}B), deposited using chemical vapor deposition (CVD) [see Fig. 1]. Since neutrons do not interact with matter through Coulomb forces and conventional semiconductor materials like silicon have a very low probability of absorbing thermal neutrons, the *Pillar* detector detects the presence of thermal neutrons through nuclear reaction products generated from neutron absorption events that occur in the ^{10}B filled regions of the device. When a thermal neutron collides with and is absorbed by a ^{10}B nucleus, the most common primary reaction products generated are alpha particles (α) and ^{7}Li ions. After generation, these high energy primary reaction products travel through the ^{10}B filled regions and enter the Si pillars where they can generate secondary reaction products (i.e. electron-hole pairs) by ionizing and exciting atoms they encounter along their path.

When operated under zero applied bias, the built-in electric field in the Si p-i-n pillars separates and collects these primary and secondary reaction products at the contacts of the device, which generate an electrical signal and indicate the initial thermal neutron interaction.

A schematic of the current design of the *Pillar* detector is shown in Fig. 1. Using this design, our group has achieved a thermal neutron detection efficiency approaching 50% for a 2 x 2 mm^2 device area. Having achieved a detection efficiency competitive with ^3He tube technologies, our next goal is to maintain this high detection efficiency when the detector area is increased from a 2 x 2 mm^2 design to a 1 x 1 cm^2 design. However, our results indicate that as our detector area is scaled upward we observe a decrease in efficiency due to an increase in noise. This suggests that our current design needs to be modified further.

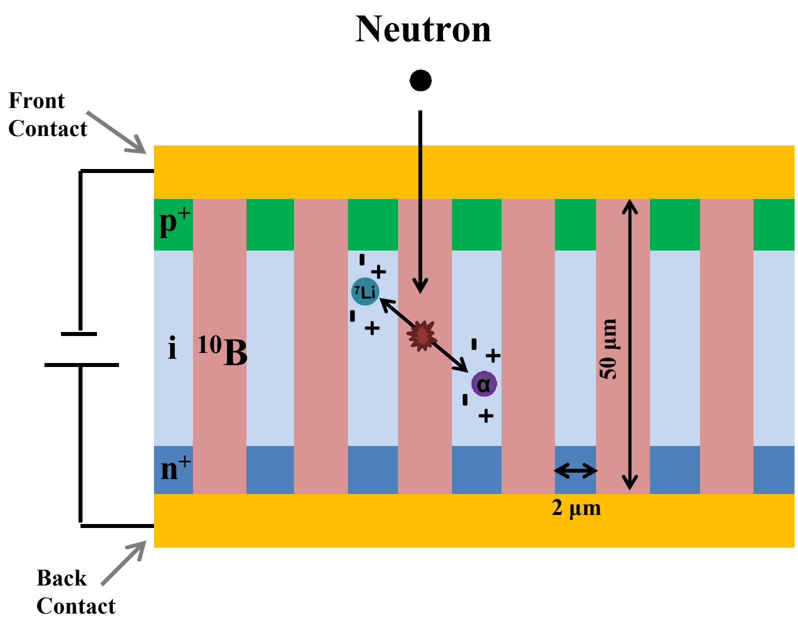

Fig. 1: Device design and fundamental operation for LLNL's silicon pillar structured thermal neutron detector.

Electronic noise is related to the detector's leakage current and capacitance. Since both leakage current and capacitance scale with device area, as the detector area is increased, the noise signal increases making it more difficult to distinguish the actual signal due to the interaction of neutrons with pillar detector from the noise. In order to create high efficiency large area detectors, our existing design needs to be modified to: 1) increase the depletion region in the Si pillars so that it extends across the entire intrinsic region and 2) passivate fixed charges (i.e. dangling bonds) that formed on the pillar side-walls during device fabrication [see Fig 2 (a)]. One way to minimize noise is to create an ultra-shallow junction (x_j) boron-diffused p+ layer which wrap around the silicon pillars [see Fig. 2(b)]. Developing a method to create this "wrap-around" layer was my assignment this summer.

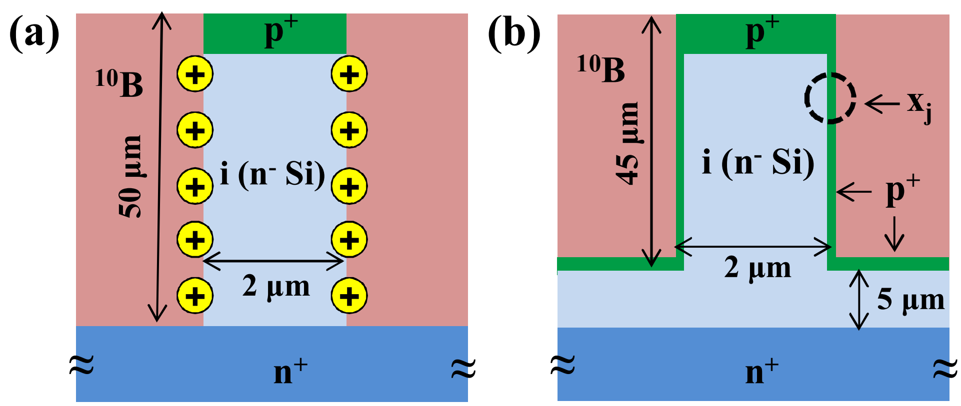

Fig. 2: Existing (a) and proposed (b) pillar designs.

At the start of my internship, I began by evaluating different conformal surface doping techniques that could be used to create this "wrap-around" p+ boron layer. Having had little experience with diffusion processing outside of the classroom, I performed a literature review on ultra-shallow junction ($x_j < 150$ nm) formation where I learned about standard tube furnace and rapid thermal annealing (RTA) diffusion techniques and various doping sources. Due to design objectives, time constraints, and equipment contamination issues, I developed an experimental plan that primarily involved rapid thermal annealing of two different doping sources: 1) a liquid boron-containing spin-on glass, 2) a liquid mixture of boric acid dissolved in methanol. These doping techniques had not been tested at LLNL prior to the start of my internship.

After receiving cleanroom training and collecting my doping source materials, I began to investigate the efficacy of each doping source using flat silicon p-i-n wafers and n-type prime silicon wafers. Since our objective was to create a boron-diffused p+ layer, the p region from starting p-i-n substrate had to be removed prior to doping. This was accomplished with wet chemical etching using an ammonium fluoride-nitric acid solution or deep reactive ion etching. After etching, the doping type and sheet resistance of the Si i-n wafer were characterized using a four-point probe technique.

Prior to doping source application, all test wafers were subjected to solvent and acid cleaning processes. Liquid doping sources were applied using spin coating techniques and baked on a hot plate before thermal processing. To achieve a shallow p+ layer, I aimed to limit the diffusion of boron in Si by using high temperatures for short periods of time. The majority of my thermal processing experiments were carried out using a rapid thermal annealing tool at $1000^{\circ}C$ for 10 – 360 s in an argon gas environment. After thermal processing, samples were cleaned and metal was deposited to create contacts for electrical measurements. Figure 3 shows the current-voltage (I-V) characteristics for four sets of samples fabricated on i-n Si wafers using the diffusion process described above. The diode-like IV curves obtained for devices fabricated using different doping sources verified that these doping techniques successfully created p-n junctions.

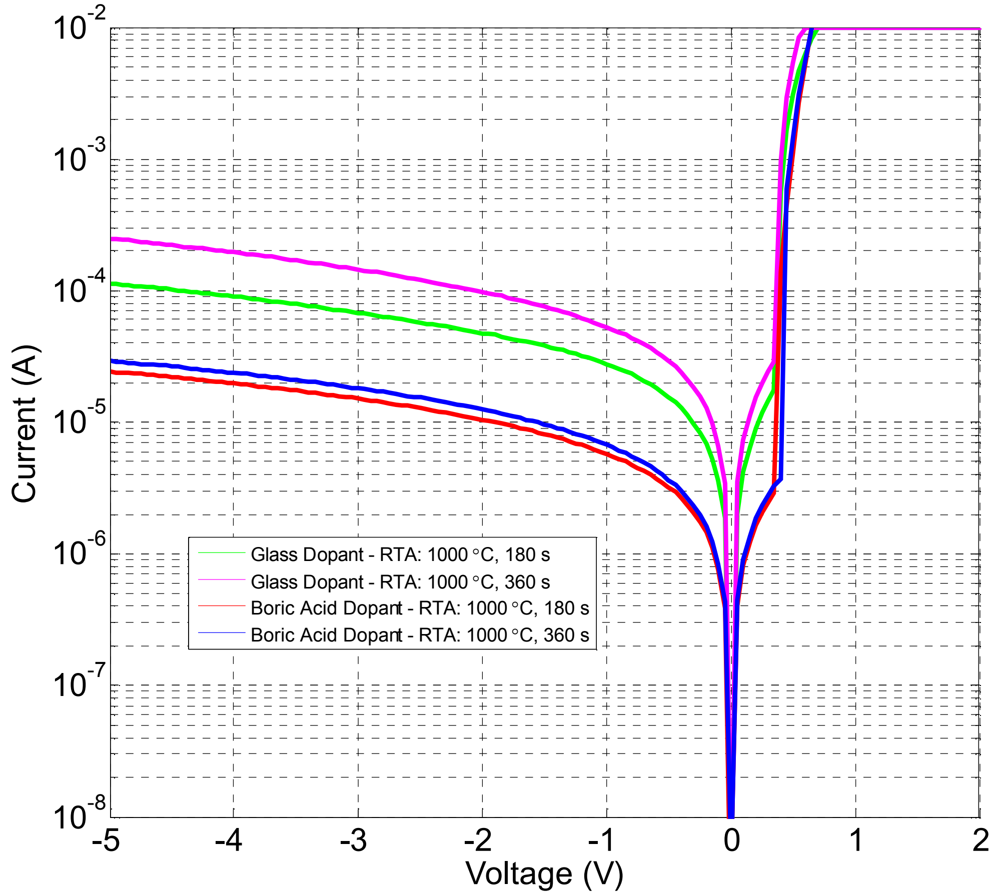

Fig. 3: Flat diode I-V curves for samples fabricated on i-n Si wafers using liquid doping sources.

After establishing that we could create p-n junctions on flat silicon wafers, I began experimenting with conformal coating of high aspect ratio test structures. “Ridge” test structures were used for my initial experiments because they can be cleaved easily for cross-sectional analysis with scanning electron microscopy, do not require planarization techniques before electrode formation, and their design is more representative of the pillar design than the flat wafer. I have tested several application and baking procedures to conformally coat the ridge structures. During the last few weeks of my internship, I demonstrated that the boron-containing glass doping source can be used to conformally coat high aspect ratio ridge structures using a drop-casting and hot plate curing technique. At the conclusion of my internship, I am working on boron-diffusion experiments for the glass coated ridges and evaluating ability of the other doping sources to conformally coat the ridge test structures.

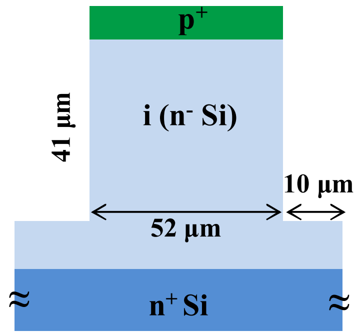

Fig. 4: "Ridge" test structures used for conformal coating experiments.

I was very fortunate to have received a two week extension of my internship which enabled me to significantly increase my contributions to this project. During my extension I was able verify that, in addition to the boron-doped glass, the boric acid doping source could also be used make p-n junctions on flat silicon wafers using our diffusion techniques. The two week extension also allowed me to work on optimizing a procedure for conformal coating of ridge test structures using boron-doped glass. This result will be important for the next phase of the project where we will begin working with pillar structured samples.

The DHS HS-STEM internship program has had a positive impact on my professional development. This program provided me with a great opportunity to expand my knowledge base and skill set while exploring a research interest that was not the current the focus of my PhD work. Over the last twelve weeks, I have gained invaluable insight and practical experience in the area of solid state radiation detection by directly interacting with experts in this field. I have been able to significantly expand my semiconductor processing skills and learn about important detector design considerations which could easily be applied to my current PhD thesis work as well as various solid state device research areas that I may be involved with in the future.

In addition to expanding my technical skills, this experience has also helped improve my communication skills by giving opportunities present on technical subject matters to diverse audiences. At weekly group meetings, I gave technical presentations to individuals who have direct knowledge of my project. During these 15-20 minute presentations, I usually described my processing experiments and any issues that I encountered during the previous week. Since these presentations were weekly, I quickly became more comfortable presenting on topics outside of my thesis work without rehearsal.

One of the most helpful events that I participated in during my internship was LLNL's Summer Student Poster Symposium which was held at the beginning of August. While I have had a fair amount of practice giving technical presentations, this event was unique in that required me to provide a basic overview of my project and summarize my results for a very general audience. As a person who enjoys details, I initially found these requirements quite challenging. However, after a few rounds of critiques from my group members, I was able break away from my normal detail oriented style and design a poster for a general audience. Since I enjoy speaking and interacting with people, I found this useful exercise to also be a very fun experience.

This internship also helped me develop a greater understanding for the scientific and engineering challenges facing our nation by attending several tours and lectures describing the diverse array of projects being studied at the lab. One of my favorite tours this summer was of the Center for Accelerator Mass Spectrometry (CAMS). As a person who works with ultra-high vacuum equipment on a daily basis for my PhD work, I was extremely impressed by the CAMS facility. Our tour guide provided a detailed explanation of the carbon-dating process and described its application to many aspects of science and technology. I was impressed by the sensitivity of the AMS technique and its ability to detect extremely low levels of ^{14}C, which dramatically reduce sample size requirements. I was surprised to learn that carbon dating is a destructive technique and quickly understood how important sample size can be when dating historical artifacts. One fact that I found particularly interesting was that carbon dating is used to determine by the age of elephant tusks. By comparing the amount of ^{14}C in ivory with the ^{14}C emissions before the import ban in 1989, scientists can determine if the elephant had died before the ban and whether or not the ivory in question can be legally imported into the USA. Aside from dating ivory, CAMS scientists are also doing some very interesting work on personalized drug delivery.

One of my favorite talks this summer was a general overview of the radiation detection technologies under development at LLNL. This subject matter is in line with my research interests and was particularly relevant to my work here at the lab. The lecturer, Simon Labov, described silicon-based, germanium-based, scintillator, and gas filled detection platforms. He also touched on how these technologies are being deployed in the field for neutron and gamma ray detection. I thought Simon's delivery was outstanding. He awarded students with *atomic fireballs* for correctly answering questions throughout his presentation. He also provided movie recommendations for us to see how Hollywood has portrayed radiation detection technology and nuclear weapons over the years.

In terms of personal development, I enjoyed attending a discussion panel on work-life balance that was organized by LLNL's women's association. In an open forum, a group of five women at various stages in their professional careers described their experiences with work-life balance. It was nice to hear all of these women agree that LLNL encourages its employees to maintain a good work-life balance by offering lab community events throughout the year, exercise classes, support groups, special interest clubs, and flexibility for family issues. As someone who has spent years preparing for a career but also wants to have a family one day, I really appreciated hearing the advice these women had to offer.

Overall, the most important outcome from my experience as a DHS HS-STEM intern at LLNL is the impact that this summer has had on my career plans. For most of my academic career, I have been uncertain about my plans after graduation. This internship program has helped me clearly establish my long-term career goals. I am now confident that I want to continue to contribute to projects which address national security by working at a national laboratory after graduation. In addition to long-term plans, the DHS HS-STEM internship program has also had an impact on my short-term career plans. At the conclusion of this program, I will become a year-round student intern at LLNL and will continue working on the *Pillar* detector project while I finish my degree.